QUANTITATIVE MICROBIAL RISK ASSESSMENT USING AZRED WATER QUALITY MODELS

by

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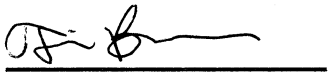
SIGNED: 

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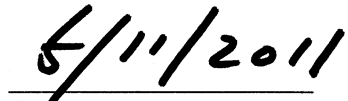

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Cryptosporidiosis is a common gastrointestinal disease that significantly impacts immune-compromised individuals. In this study, water quality analysis and dose-response models are used to calculate the location-based risk of *Cryptosporidium* infection within 24 hours of an intrusion into a drinking water system. Current water quality models such as EPANET are based upon two main assumptions: complete mixing occurs at pipe cross junctions, and axial dispersion of a solute does not occur along the length of a pipe. To improve the accuracy of EPANET, two newly developed models, AZRED I and II, consider these assumptions. EPANET-generated simulations model plug flow—the movement of large contaminant concentration pulses with respect to time—while AZRED-generated simulations model solute dispersion, which results in lower contaminant concentrations over a longer period of time. The risk of infection was calculated for populations at four specific locations in a network using an exponential model. Results obtained using AZRED, when compared to results obtained from EPANET, predicted a higher risk of infection at downstream locations.

CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Cryptosporidiosis

Cryptosporidiosis is a gastrointestinal disease caused by the parasite *Cryptosporidium*. *Cryptosporidium* thrives in the intestines of humans and other animals such as farm animals, cats, and dogs, and it is evident that an infected person releases the *Cryptosporidium* parasites through stool. *Cryptosporidium parvum* is the species of the parasite that is associated with the infections in humans. *Cryptosporidium* is contracted by ingesting potentially anything that has come into contact with infected stool. Transmission through water, specifically, can occur in recreational venues or through drinking water (Centers for Disease Control, 2009). This parasite is resistant to chlorine and is the most common cause of waterborne infection in the United States. *Cryptosporidium* is so hardy that it can survive in the same environment for months at a time, even with slight variation in temperatures, although the parasite cannot survive freezing temperatures or temperatures above 18 degrees Celsius (Fayer, 2008). Additionally, it is among the most common causes of diarrhea (Harms, 2009). The infectious dose of *Cryptosporidium* for humans is between 10 and 100 oocysts (Meinhardt, 1996).

Cryptosporidiosis was recognized as a gastrointestinal disease in 1976. However, it did not gain nationwide attention until 1993 when a massive outbreak occurred in Milwaukee, Wisconsin. During this outbreak, over 400,000 of the 1.6 million Milwaukee

residents fell ill with diarrhea, and over 2,000 died (Harms, 2009). The cause of the outbreak was studied by Mac Kenzie et al. (1994). This study concluded that *Cryptosporidium* oocysts were present in untreated water from Lake Michigan. These oocysts had entered the water treatment plant and traveled through the system undetected. As a result of the study, water quality standards were questioned, and improvements were considered. Additionally, a means of continuously monitoring treated water for turbidity and other possible contaminant characteristics was in consideration. The detection of oocysts is important, as well as the prediction of exposure time in order to prevent outbreaks such as the Milwaukee occurrence.

This paper focuses on *Cryptosporidium* transmission specifically through drinking water systems, the most common transmission mechanism of *Cryptosporidium.* Additionally, dose-response models are included in order to present a risk assessment study combining advanced water quality models with realistic *Cryptosporidium* dose-response data.

1.1.2 Water Consumption

Drinking water consumption patterns in a population are a significant factor to include in a realistic risk assessment study. A study by Barraj et al. (2009) discusses drinking water consumption over a one-day period—specifically, the time of consumption, the amount consumed, the location at which the water was consumed, and the type of water consumed. The drinking water consumption patterns of individuals across the nation were compiled based on survey results. This study will take into

consideration the United States Environmental Protection Agency's drinking water intake guideline, which estimates a rate of 2 liters per day per adult. This rate is representative of a measure of tap water intake, which includes water taken directly from the tap either for beverage consumption or for food and beverage preparation. Tap water consumption, rather than total fluid intake, which includes water in addition to other beverages, is a more accurate means of measuring the potential exposure to infection, because total fluid intake may overestimate the risk (Wood, 1997).

1.2 Water Quality Modeling Systems

1.2.1 Current Water Quality Modeling: EPANET

The water quality model utilized in this study is EPANET, a widely used water quality modeling program that performs hydraulic and water quality analysis. EPANET is an easily accessible program that can be downloaded from the United States Environmental Protection Agency website. In addition to a user-friendly interface for editing input data, EPANET offers a programmer's toolkit, which allows further use in water distribution system-related research. For this particular research study, EPANET is used to model a network in which a *Cryptosporidium* intrusion has occurred. Nodes, or pipe junctions, which represent a population cluster, are analyzed for *Cryptosporidium* concentration, depending upon the demand at that particular node. The demand value represents the amount of water being extracted from the node. Using EPANET, the demand, intrusion concentration of *Cryptosporidium*, and overall layout of the pipe networks can be altered to suit the desired scenario. For this study, EPANET is used to

calculate the concentration of *Cryptosporidium* at a particular node at each hour within 24 hours of the initial intrusion.

Current water distribution systems modeling is based upon two significant water quality assumptions. The first assumption is in regards to solute or contaminant mixture at pipe cross junctions. Current models assume that solutes mix completely and evenly at cross junctions. The second assumption is associated with solute concentration along the distance of a pipe. Current models include the assumption that solute concentration is equal along the length of a pipe. This convenient simplification, referred to as plug flow, envisions the solute traveling at a constant velocity across any cross-section of the pipe perpendicular to the axis of the pipe. Additionally, plug flow depends on the assumption that there is no boundary layer on the inner wall of the pipe. In contrast, realistic pipe flow displays axial dispersion—a phenomenon in which solute spreading and dilution occurs throughout the pipe cross section.

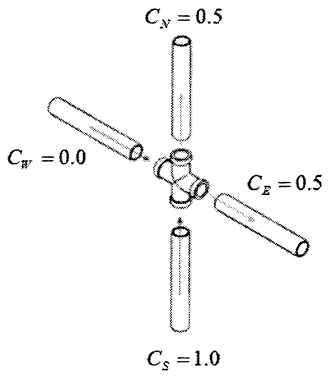

Figure 1.Complete mixing at a pipe four-way cross junction.

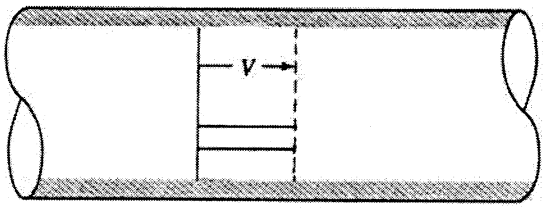

Figure 2. Plug flow along a pipe cross-section.

1.2.2 Newly Developed Water Quality Models: AZRED I

The two major water quality assumptions have been extensively studied at the University of Arizona, Tucson, AZ, U.S.A. The first assumption, mixing at cross junctions, was researched via both numerical and experimental studies. The numerical study was performed using computational fluid dynamics simulations, while the experimental study involved a series of experiments set up to acquire solute concentrations in a water network configured to produce fully developed turbulent flow. Both of these studies concluded that solutes at cross junctions do not mix completely, and that such assumptions can cause inaccuracies in water quality modeling (Romero-Gomez, 2008; Austin, 2008). Figures 3 and 4 exemplify incomplete mixing. In both figures, clean water enters the system from the west, and contaminated water, represented in red, enters from the south. It is exhibited by the two exit junctions that the majority of contaminated water travels to the east.

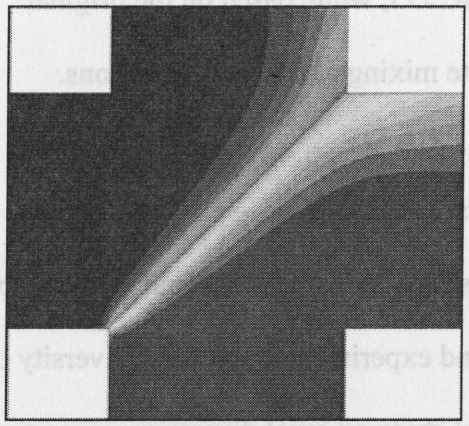

Figure 3. Incomplete mixing at a cross junction via computational fluid dynamics.

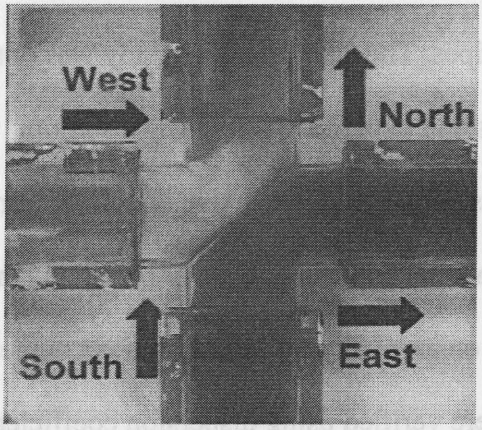

Figure 4. Incomplete mixing at a cross junction via experimental results.

Numerical and experimental results did not exhibit complete and instantaneous mixing at four-way junctions; rather, the results presented the idea that incomplete mixing occurs at pipe cross junctions. Hence, incorporating this novel factor of incomplete mixing into water quality modeling analysis will allow for improved calculations.

The Choi research group at the University of Arizona, Tucson, AZ, U.S.A. developed AZRED I, a modified version of EPANET which takes into consideration

incomplete mixing at four-way junctions. AZRED I, while based on the original EPANET source code, incorporates incomplete mixing at four-way junctions.

1.2.3 Newly Developed Water Quality Models: AZRED II

The second major assumption involves the issue of longitudinal solute dispersion. This has also been studied both numerically and experimentally at the University of Arizona Water Village. One such experimental study on axial dispersion properties was performed by Sinclair et al. (2009). This particular study used MS-2, a coliphage, to examine virus patterns in water distribution pipes. The data from this study was obtained numerically via computational fluid dynamics and experimentally using a sodium chloride tracer. Under laminar flow conditions, significant dispersive effects occurred. Romero-Gomez et al. (2010) performed another axial dispersion study based on laminar flow over short distances. This study focused on axial dispersion analysis via numerical equations, and existing transport equations were verified using dispersion coefficients. The dispersion coefficients were analyzed and then utilized to develop a new equation for solute transport. Both of these axial dispersion studies demonstrated the importance of including dispersive components in water quality models in order to obtain more accurate predictions, especially for quantitative risk assessments.

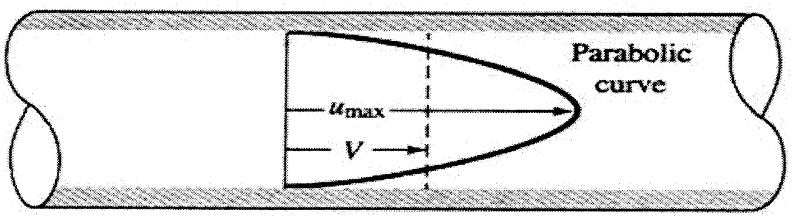

Figure 5. Axial dispersion in laminar flow conditions.

As shown in Figure 5, solutes exhibiting dispersive properties travel quickly along the centerline of the pipe, but lag along the pipe wall. Contaminants attached to the pipe wall facilitate the development of biofilm, which occurs when organisms stick to pipe walls. Biofilm debri can enter a drinking water system and become a significant health-related issue. If a water system were to shut off abruptly, such as, for example, during a power outage, and then was turned on quickly, the initial water velocity rushing through the system would be much greater and could flow with enough force to cause biofilm to slough off of the pipe walls and mix with the water, thus posing the potential to impact consumers.

It is especially important to consider solute travel in a laminar flow water system in order to accurately calculate the exposure time of the contaminant. The first step in predicting and preventing waterborne *Cryptosporidium* infection is to take into account the flow speed and the contaminant travel pattern in the pipe network. Waterborne infection prediction is based on contaminant concentration, exposure time, and contaminant infectivity. Figure 6 exhibits the significant impact that flow conditions have on concentration versus time.

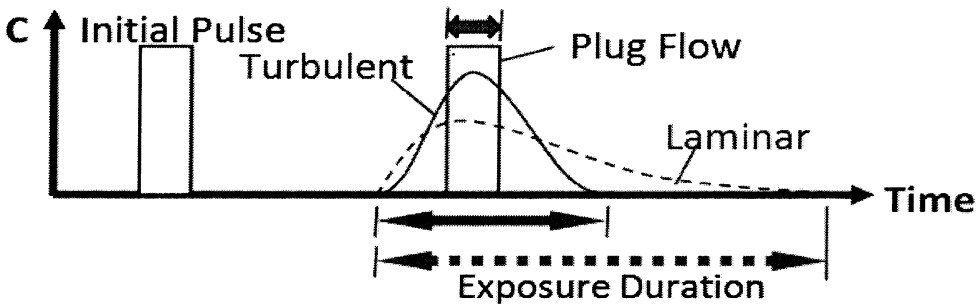

Figure 6. Concentration versus exposure time in various flow conditions.

Figure 6 is a graphical representation of the significance of accurately calculating the presence of pathogen in the water system. Depending upon the species of the pathogen, exposure duration could play a significant role in preventing waterborne illness caused by a pathogen intrusion. For example, no evidence exists that exposure to a single oocyst of *Cryptosporidium* has ever caused an infection in a human (Messner, 2001). The infectivity observed for *Cryptosporidium*, in fact, occurs between 10 and 100 oocysts; therefore, when the axial dispersion model is used in conjunction with laminar flow conditions, *Cryptosporidium* will not exhibit a high infectivity level for the entirety of the exposure duration. In other words, *Cryptosporidium* tends to infect only when a high amount of oocysts are ingested. And thus, for *Cryptosporidium*, predicting higher levels of oocysts in the water system becomes important. For other pathogens which can cause harm in a small concentrations, exposure duration time is an important consideration, one that should not be underestimated.

AZRED II is a recently developed extension of EPANET. AZRED II accounts for incomplete mixing at four-way pipe junctions and also for axial dispersion. AZRED II is

novel in that it considers the changing concentrations of a substance moving downstream in a water system by including dispersion coefficients. This program could have an enormous positive impact on public health issues associated with the ingestion of chemical and biological contaminants.

1.3 Risk Assessment Studies

Cryptosporidiosis risk models have been developed by many risk assessment groups. These groups focused on infectivity versus pipe flow. One such model, established by Casman et al. (2000), tracked the occurrence of drinking water-borne Cryptosporidiosis. Specifically, the study focused on turnaround time in relation to the outbreaks occurring in spite of response methods that are currently in use. An unusual feature of the study was the emphasis on population morbidity in relation to the timing of intrusion events. Our study focuses on infectivity rather than morbidity. Additionally, while emphasizing the timing of intrusion events, our use of advanced water quality modeling tools makes this study unique in the risk assessment field.

1.3.1 QMRA

Quantitative microbial risk assessment (QMRA) uses pathogen concentration and an exposure level to determine an associated risk of infection. The risk of infection can be calculated as a daily or annual risk. Signore and Ashbolt (2009) calculated the daily risk of pathogenic waterborne infection, rather than the annual risk of infection. Waterborne disease outbreaks—such as Cryptosporidiosis—are often associated with shorter periods

of increased risk. Hence, microbial risk assessment is important when analyzing the impact that microbial variation may have on the risk of infection.

Stine et al. (2011) also performed experiments relating to daily risk of infection with regard to viral and bacterial pathogens found on the surface of produce. This risk assessment was performed using the annual risk guideline established by the United States Environmental Protection Agency. This particular guideline states that the acceptable risk of infection due to drinking water consumption is 1:10,000 (Regli, 1991). The EPA guideline was also used to determine the acceptable dose of microorganisms consumed. The daily acceptable risk was first calculated using an exponential dose-response equation:

$$P_i = 1 - \exp(-k * dose)$$

where P_i represents probability of infection, k represents the exponential dose-response parameter, and d represents the dose of microorganisms present (Rose, 1991). Our study is based on a similar approach, in which the daily risk of infection for a population is calculated using an exponential dose-response model.

1.3.2 Dose-Response Models

Dose-response studies analyze the relationship between the dose of contaminant ingested and the effects of that ingestion. The impact that the contaminant dose has on the individual who ingests the contaminant—either infection or mortality—is measured. However, each dose-response study varies in its definition of infection.

Beta-Poisson and exponential models are typically used for dose-response studies as a means of quantifying the hazard that a certain contaminant concentration presents to a human population. The model chosen plays a significant role in the outcome of the risk assessment. While the beta-Poisson model, a two-parameter model, is more flexible than the exponential model in terms of fitting data, the current study will include an exponential, pooled model. The exponential model was chosen because it is a simpler dose-response model involving only one parameter, and for this study, is a better choice for a dose-response model. In a study by Teunis et al. (2000) the beta-Poisson model was used to extrapolate dose-response data to low doses. To decrease error that might be produced by unknown properties, the authors attempted to utilize a single-hit model, which would reduce the risk of error. It was found that the beta-Poisson model cannot be analyzed as a single-hit model. In our study, uncertainty is not taken into consideration, as a single parameter value is used for each simulation.

Another study by Teunis et al. (2002) tested three different *Cryptosporidium* isolates for infectivity variation. Data on the infectivity variation among isolates was retrieved; if a specific isolate is more virulent than the others, a more detrimental outbreak can occur. Quantifying the *Cryptosporidium* isolate virulence and infectivity could facilitate prevention methods that employ risk and exposure assessment techniques.

1.3.3 Model Utilized

The model utilized in this study is a Bayesian hierarchical exponential model. The dose-response models and parameter values were provided by Mitchell-Blackwood

and Gurian from Drexel University, Philadelphia, PA, U.S.A. The development of Bayesian analysis has allowed dose-response analysis to become less complex. For its analysis, this approach utilizes information drawn from related studies to obtain an array of parameter values. Risk estimation can be calculated with a Bayesian model using an infectious dose obtained from pathogen isolate data (Messner, 2001).

The Bayesian model differs from a classical statistical model, such as maximum likelihood estimation. In the Bayesian approach, parameters are treated as random variables rather than fixed values. Our study takes into account the dose-response exponential function parameter *k*, which represents infectivity. For the simulations included in this study, this particular parameter is significant. Because the Bayesian hierarchical approach is realistic, it is advantageous to use for this particular study. While a number of experiments have been performed in the effort to provide some form of evidence that proves a parameter value, not all possible experiments have been performed. This uncertainty was taken into consideration when the Bayesian hierarchical model was used to generate the *k* values included in the risk assessment portion of this study (Mitchell-Blackwood, 2010).

1.3.4 Parameter Values

The dose-response parameter, *k*, represents the infectivity of a single organism, which in this case, is *Cryptosporidium*. Our study will include the probability of infection with two different *k* values: the 95th percentile and the median values. The 95th percentile estimate provides highly conservative estimates of infectivity, which may represent

worst-case situations. A number of *k* values were determined based on experimental and statistical analysis performed on *Cryptosporidium* isolates. Of the *k* values, 95th percentile represents the highest level of infectivity, because the estimate of infectivity is greater than any that were observed for any of the products in the data set. For this reason, the median *k* value was also considered in the analysis for comparison (Mitchell-Blackwood, 2010).

1.4 Significance

1.4.1 Distinguishability

Our study combines water quality modeling with dose-response models in order to quantify the probability that a *Cryptosporidium* infection will occur when the parasite enters a water distribution system. What further distinguishes this research is the use of AZRED versus EPANET, and AZRED II, specifically, will play a major role in this study. This recently developed water quality model takes into consideration axial dispersion of a solute moving downstream. In this case, the substance will be *Cryptosporidium*. By using AZRED, the simulations of *Cryptosporidium* concentrations in various locations in the network can be modeled more realistically, and hence, more accurately.

1.4.2 Interdisciplinary Study

Utilizing AZRED water quality models and risk assessment techniques, this study is a pioneering one that can truly be called interdisciplinary because the project integrates

engineering and statistical techniques as a means of combating significant public health hazards. Dose-response studies involve analyzing various exposure concentrations and the effects the doses of contaminant have on an individual. In these studies, the risk of infection is calculated. However, with the integration of water distribution systems, the risk of infection at a particular location after a contaminant intrusion can be calculated. This ability takes traditional dose-response studies one step further than previously has been done.

1.4.3 Objective

Our study aims to quantify *Cryptosporidium* infection at a specific location in a network within a 24-hour span after an intrusion has occurred in the water distribution system. Additionally, business and residential area water use and consumption patterns are taken into consideration. Realistic infectious dose levels of *Cryptosporidium* oocysts are also included in the simulation. This is a time-dependent, dose-response, location-based risk assessment, and exposure analysis combination. Taking into consideration contaminant concentrations in the water system at four-way junctions, and also axial dispersion, this novel study will provide accurate information in order to predict the risks of infection. Additionally, data analysis from this study will greatly enhance measures intended to prevent infection and, perhaps in the future, eliminate all risk of infection after a *Cryptosporidium* intrusion in a water system.

This study seeks to integrate dose-response models with contaminant distribution of *Cryptosporidium* via a water quality analysis software program, which in this case is

EPANET. A single, carefully chosen dose-response parameter is utilized, rather than a distribution of values, since this particular study does not include uncertainty in the dose-response models. The 95th percentile was chosen as the primary parameter value over the median and 5th percentile values because the Bayesian hierarchical model has a tendency to underestimate risk, and the 95th percentile tends to overestimate risk.

The hypothesis of this study is that simulations performed utilizing AZRED II, compared to those conducted using EPANET, will show that the concentration of *Cryptosporidium* in a water distribution system will persist for a longer period of time after an intrusion, and that the corresponding risk of infection at a particular location will increase over a span of 24 hours.

CHAPTER 2

METHODS

2.1 Scenario Setup

2.1.1 Default Demand Pattern

EPANET includes a built-in demand pattern that represents the water usage during a 24-hour period at every node that contains a population. A demand pattern consists of a series of constants called demand multipliers for every hour. When the demand multipliers are multiplied by the base demand, the total demand at that particular hour is given. In Figure 7, the demand multiplier at 6:00 AM is the highest and indicates the highest overall demand at that hour relative to the other hours. The demand pattern graph displays the overall relative usage over the span of one day.

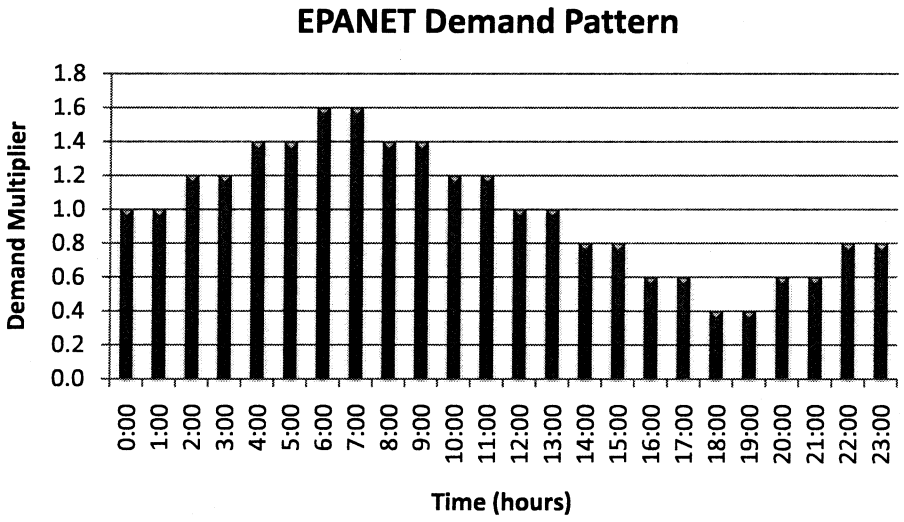

Figure 7. EPANET default demand pattern.

Since this study focuses on assessing risk in a realistic scenario, the EPANET default demand pattern is not used. Rather, a more realistic demand pattern, one that represents usage during a 24-hour span, was developed.

2.1.2 Realistic Demand Pattern

The demand pattern utilized in this study is based on one developed by Blokker et al. (2010). This pattern is a realistic representation of average water use over the span of 24 hours. The graph below displays relative hourly water usage.

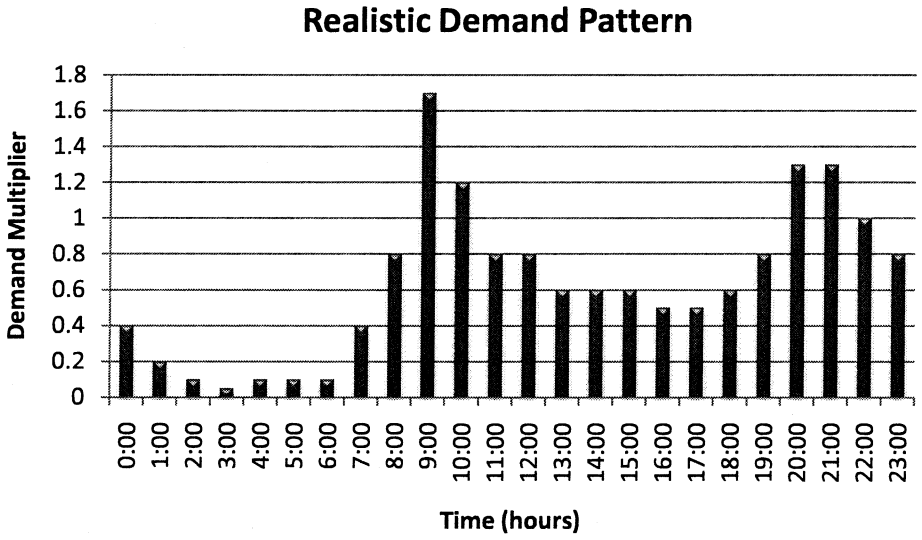

Figure 8. Realistic water usage pattern.

2.1.3 Water Consumption Pattern

This study combines risk assessment techniques with water quality analysis. Demand patterns are necessary for the water quality analysis portion of the study. However, to assess the risk presented by a pathogen that causes infection via water

consumption, a water consumption pattern must also be taken into consideration. The consumption pattern utilized in this study is based on one developed by Barraj et al. (2009). The pattern is a realistic representation of average per capita water consumed during a 24-hour period. The study was based on a water consumption survey of individuals in the United States. It included the amount of water consumed at each hour during the course of a day. The authors compiled the data into graphical form. According to the United States Environmental Protection Agency, the average American consumes two liters of water per day. Hence, the consumption pattern included in this study apportions two liters over the entire 24-hour span (U.S. EPA, 2006).

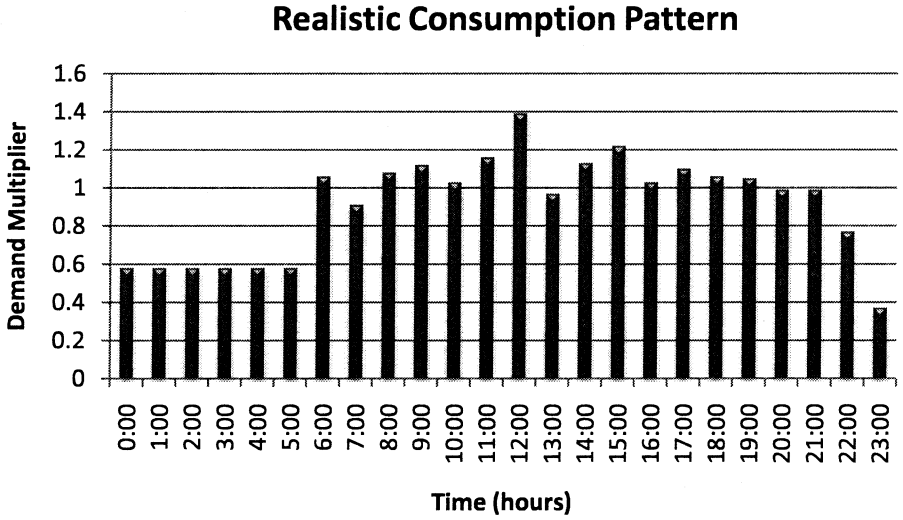

Figure 9. Realistic water consumption pattern.

2.1.4 Base Demand

The base demand, a necessary input parameter when using the demand pattern, represents the base water usage in terms of flow rate. This value determines the flow rates

that follow, based upon the demand pattern. The base demand included in this study was obtained from Blokker et al. (2010). The authors of the study measured a base demand of 151.14 gallons per minute (GPM) for a population of 3,000 in a residential area. Under the assumption that an average of three people reside in each home, the demand for this study was proportioned and modified for smaller populations. The resulting base demands utilized in this study are 2.915 GPM and 5.83 GPM for populations of 50 and 100 people, respectively.

2.2 Water Quality Modeling Simulations

To perform simulations in order to calculate contaminant concentration, several parameters were taken into consideration: pipe diameter, pipe length, base demand, and *Cryptosporidium* intrusion concentration. These specific parameters were set in order to ensure desired flow conditions—laminar or turbulent—throughout the entire simulated network. The newly developed AZRED II ensured the inclusion of axial dispersion calculations during laminar conditions, and has yet to be developed for transitional and turbulent flow. As a result, the simulations performed in this study focus primarily on laminar flow conditions. Laminar flow is significant in that it is typical of water flow in the middle of the night, in a small neighborhood, or in a cul de sac.

2.2.1 Simple One-Line Network

The first simulations were performed in a simple, one-line network which included two locations with populations: nodes 12 and 13.

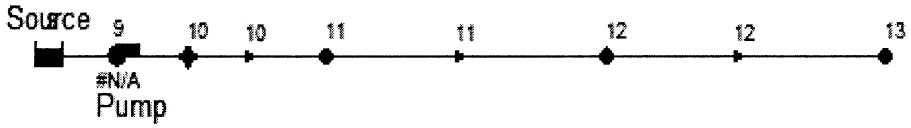

Figure 10. Simple network.

In the simple network simulation, the *Cryptosporidium* intrusion was a pulse that occurred at Node 10 at midnight. The pulse continued for one hour at a concentration of 1 oocyst/Liter. Nodes 12 and 13 had populations of 750 people, each with a base demand of 37.7855 GPM. Diameters were set in order to accomplish turbulent flow conditions from node 10 to node 12 and laminar flow conditions from node 12 to node 13. This was done in order to make a clear distinction between plug flow effects and dispersion effects when comparing all three water quality models: EPANET, AZRED I, and AZRED II. The simulation was for 24 hours.

2.2.2 Expanded Simple Network

The next simulations involved expanding the simple network to incorporate a cross junction to convey AZRED I effects. The network is shown below.

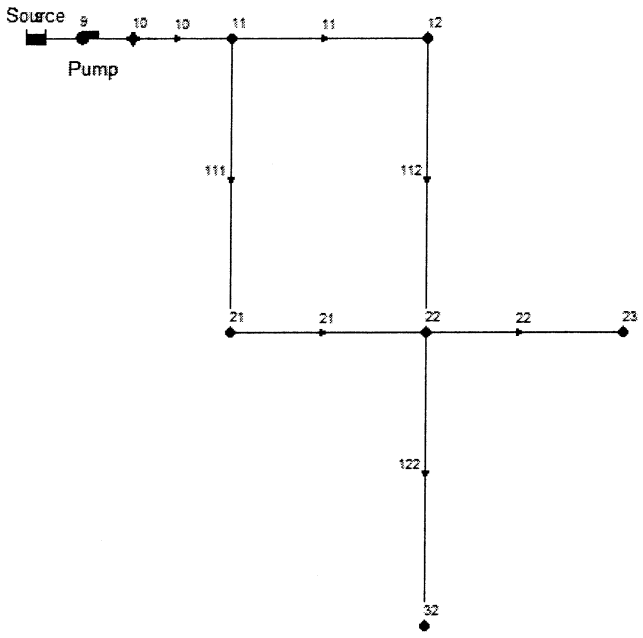

Figure 11. Expanded network.

Similar to the simple node network, the *Cryptosporidium* intrusion occurred at node 10 in pulse-like fashion for one hour at a concentration of 1 oocyst/Liter. Nodes 23 and 32 each contained populations of 500 people. The diameters were altered in order to produce laminar flow throughout the entire network. Simulations were performed using EPANET, AZRED I, and AZRED II for 96 hours. The simulation time was extended in order to see the full effects of dispersion when using AZRED II.

2.2.3 Complete Network

The network was expanded to its entirety and in accordance with the design of EPANET Example Network 1. The complete network is shown in Figure 12. The intrusion location, time, and length remained the same as those used for the previous

simulation. This network included populations at nodes 13, 21, 23, and 32, and each population contained 500 people. Diameters were altered to reflect uniformity in order to ensure that flow was occurring through all pipes and that stagnant flow did not occur at any period of time. Simulations were performed using EPANET, AZRED I, and AZRED II.

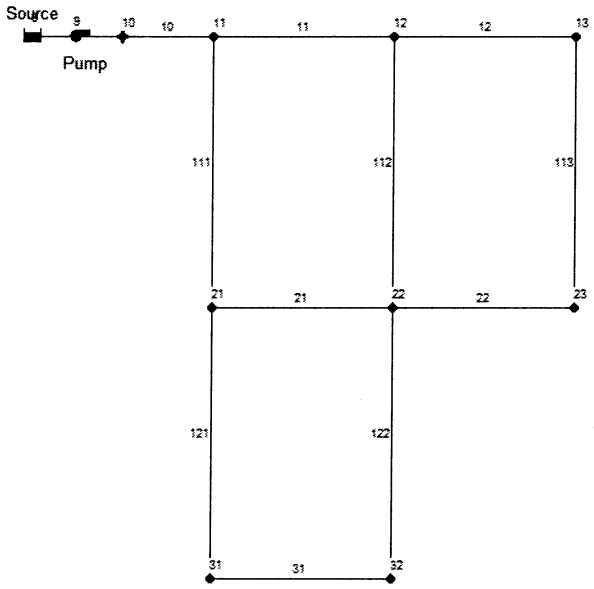

Figure 12. Complete network based on EPANET Example Network 1.

2.2.4 Determination of Accuracy

The simple node network was simulated again to ensure that the accuracy of the concentrations obtained via AZRED II was comparable to that of the established water quality program, EPANET. The accuracy was measured using principles of mass balance: the mass entering the system is equivalent to the mass leaving the system. The mass entering the system is determined by measuring the initial *Cryptosporidium*

intrusion, and the mass out of the system is determined by measuring the nodal demands. The mass balances were calculated during a 72-hour simulation using EPANET, AZRED I, and AZRED II, and the respective percent errors were determined. The troubleshooting process is discussed in its entirety in the Appendix.

The best possible scenario was determined by modifying and testing the parameters discussed in the Appendix. Then, the complete simulation was run with the expansion of the simple network to its full extent which is in accordance with the EPANET Example Network 1. Based on the test results, several factors were considered: laminar flow, a Reynolds number of at least 1500 for the majority of the pipes, a 24-hour simulation period, and a low quality tolerance.

2.3 Inclusion of Dose-Response Models

2.3.1 Dose Calculations

Cryptosporidium concentrations were obtained by generating the aforementioned simulations with EPANET and AZRED II. Concentration data was obtained at each population node, every hour, for 24 hours. Table 1 below exemplifies the concentration data collected.

Table 1. *Cryptosporidium* concentration versus time.

Time (hours)	Concentration (mg/L)	Time (hours)	Concentration (mg/L)	Time (hours)	Concentration (mg/L)
0:00	0	8:00	0.349696	16:00	0.023585
1:00	0	9:00	0.297438	17:00	0.023671
2:00	0	10:00	0.213122	18:00	0.023643
3:00	0	11:00	0.125252	19:00	0.023623
4:00	0.00026	12:00	0.059913	20:00	0.023627
5:00	0.033505	13:00	0.029156	21:00	0.023631
6:00	0.152572	14:00	0.024833	22:00	0.023633
7:00	0.30256	15:00	0.024292	23:00	0.023636
				24:00	0.02363

Risk of infection at a particular node is calculated by multiplying the concentrations obtained from the simulations by the consumption pattern. This represents an overlap in water usage and consumption. The concentration of *Cryptosporidium* at each node depends upon the water usage at the node, while the risk of *Cryptosporidium* infection depends upon the amount of water consumed by the population at the node. Concentration, multiplied by the consumption pattern, produces a mass flow rate, represented as oocysts/hour. The mass flow rate is then distributed over 24 hours to determine the mass that the entire population of the node ingests in one day. This is then used to calculate the mass that one person in the node ingests over the course of one day.

2.3.2 Risk calculations

The risk of infection was calculated using the following exponential equation:

$$Risk = 1 - \exp(-k * dose)$$

where *dose* represents the mass of *Cryptosporidium* ingested and k represents the exponential parameter value. This study calculates risk with a method that uses the 95th

percentile k value and the median k value and is based on extensive dose-response studies performed by Mitchell-Blackwood et al. (2010). The 95^{th} percentile k value included in this study is 0.0577 and the median k value is 0.00241. Risk of infection was calculated for the entire population and proportioned to estimate individual risk of infection.

CHAPTER 3

RESULTS

3.1 EPANET vs. AZRED II

This study involved numerous rounds of testing in order to accurately compare EPANET and AZRED II water quality programs; hence, numerous results were generated. The following results demonstrate the major graphical and numerical differences between the programs.

3.1.1 Simple One-Line Network

The purpose of the initial simulations was to observe the general differences between EPANET and AZRED II under laminar flow conditions, namely, that EPANET's results pertain to plug flow, while AZRED II demonstrates dispersive effects. The graphical results are shown in Figure 13. In terms of the *Cryptosporidium* concentration, EPANET displays a high concentration for a short period of time, while AZRED II displays a lower concentration over a longer period of time.

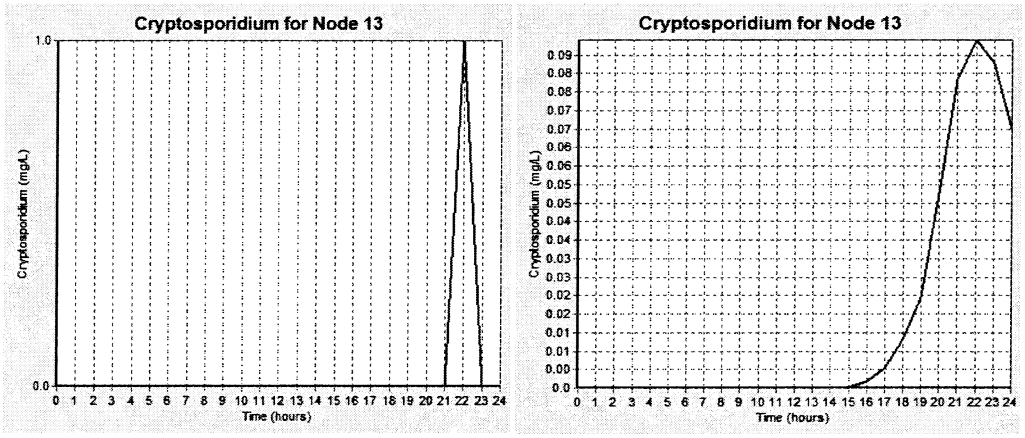

Figure 13. Left: Plug flow exhibited by EPANET. Right: Dispersive effects exhibited by AZRED II.

3.1.2 Expanded Network

After observing the effects of axial dispersion in a single pipe, the simulations were run in an expanded network in order to observe the effects when cross junctions were included. Figures 14 and 15 exhibit the concentration data analyzed for three nodes in the expanded network.

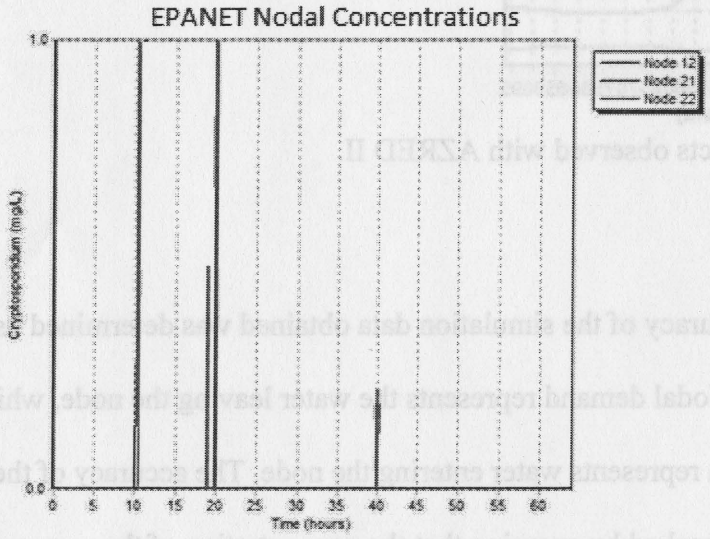

Figure 14. Plug flow observed with EPANET.

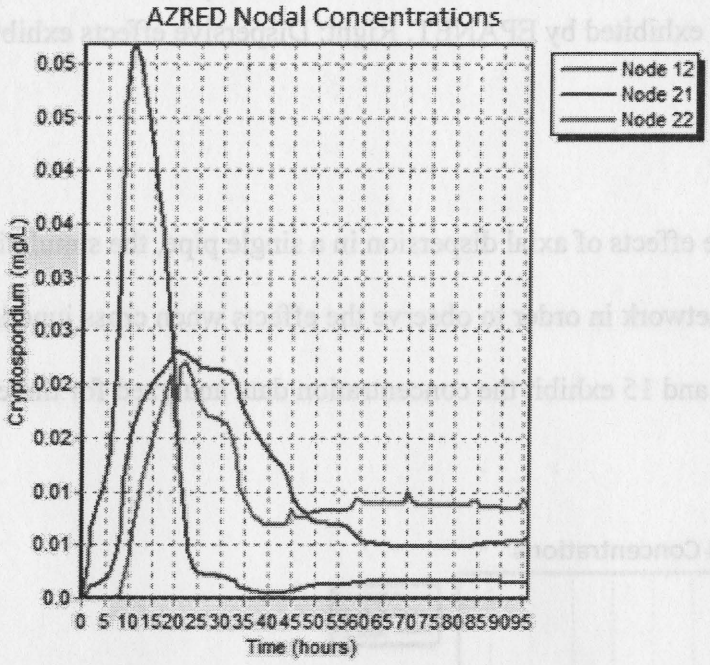

Figure 15. Dispersive effects observed with AZRED II.

3.1.3 Mass Balance

The numerical accuracy of the simulation data obtained was determined using mass balance equations. Nodal demand represents the water leaving the node, while the *Cryptosporidium* intrusion represents water entering the node. The accuracy of the water quality calculations was checked by ensuring that the concentration of the mass when it entered the system was equal to concentration of the mass when it left the system. Subsequent errors were determined to ensure uniform accuracy between the EPANET and AZRED models. Table 2 is an example of the mass balance and error calculated. The troubleshooting process, complete mass balance analyses, and potential causes of error are discussed in detail in the Appendix.

Table 2. Mass balance table with corresponding error.

Node	Mass In (mg)	Mass Out (mg)	Percent Error
10	3772.89	0.00	
13	0.00	639.06	
21	0.00	615.57	
23	0.00	1314.09	
32	0.00	1256.82	
Total	3772.89	3825.53	1.40

3.2 Risk Assessment

The risk of infection via *Cryptosporidium* was calculated using the concentrations obtained from the aforementioned simulations generated by EPANET and AZRED. The 24-hour scenario was set up to mimic an intentional intrusion situation. The *Cryptosporidium* intrusion concentration for the microbial risk assessment was 50 oocysts per liter, where one oocyst is equivalent to one milligram. This concentration was pulsed into the system for one hour.

Cryptosporidium concentration tables were generated for each population node using EPANET and AZRED II. The results are shown in Tables 3 and 4.

Table 3. Node 21 hourly concentrations with EPANET.

Time (hours)	Concentration (mg/L)	Time (hours)	Concentration (mg/L)	Time (hours)	Concentration (mg/L)
7:00	0	15:00	0	23:00	0
8:00	0	16:00	50	0:00	0
9:00	0	17:00	0	1:00	0
10:00	0	18:00	0	2:00	0
11:00	0	19:00	0	3:00	0
12:00	0	20:00	0	4:00	0
13:00	0	21:00	0	5:00	0
14:00	0	22:00	0	6:00	0
				7:00	0

Table 4. Node 21 hourly concentrations with AZRED II.

Time (hours)	Concentration (mg/L)	Time (hours)	Concentration (mg/L)	Time (hours)	Concentration (mg/L)
7:00	0	15:00	12	23:00	0.07
8:00	0	16:00	11.43	0:00	0.04
9:00	0	17:00	9.71	1:00	0.03
10:00	0.02	18:00	7.12	2:00	0.03
11:00	0.5	19:00	4.09	3:00	0.02
12:00	3.11	20:00	1.35	4:00	0.02
13:00	6.85	21:00	0.39	5:00	0.02
14:00	10.43	22:00	0.15	6:00	0.02
				7:00	0.02

Figure 16 is a graphical representation of the data presented in Tables 3 and 4. The differences between the calculated concentrations of *Cryptosporidium* in EPANET versus AZRED II are clearly shown in the graph.

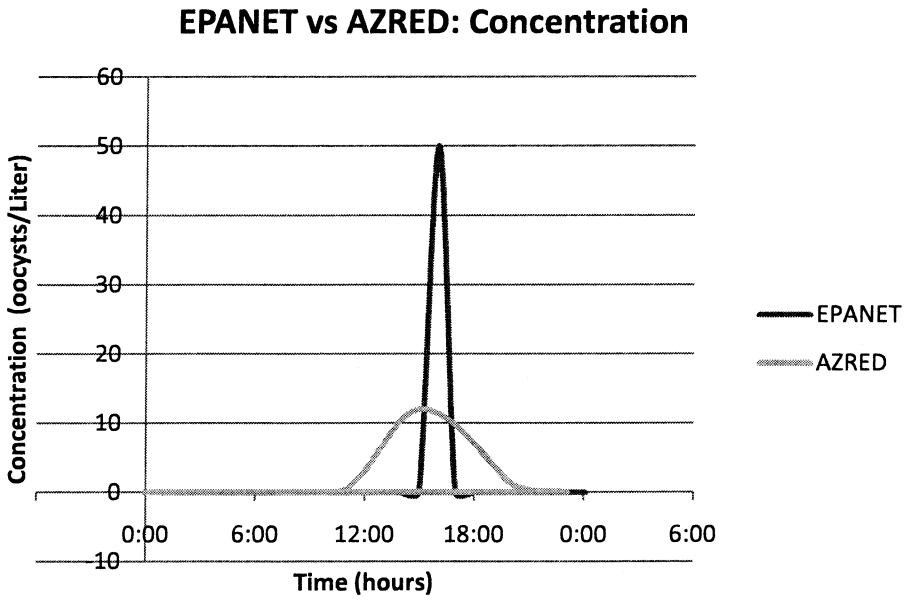

Figure 16. Comparison of EPANET and AZRED II: Node 21 concentrations over 24 hours.

The concentration data was multiplied by the consumption pattern to obtain the mass flow rate. Nodal *Cryptosporidium* concentration, consumption pattern, and mass flow rate were used to calculate the mass of the contaminant consumed by the population at each node, and then the subsequent risk of infection was determined. Data was collected for the entire nodal population, and this data was used to determine the probability of infection for each individual. The risk calculations determined by this study are location-based.

Table 5. Risk of infection with EPANET.

Node	Mass Ingested (mg)	Risk (95^{th} percentile)	Risk (median)
13	7.63	0.356	0.018
21	8.77	0.397	0.021
23	5.01	0.251	0.012
32	4.11	0.211	0.010

Table 6. Risk of infection with AZRED II.

Node	Mass Ingested (mg)	Risk (95th percentile)	Risk (median)
13	7.21	0.340	0.017
21	7.82	0.363	0.019
23	6.12	0.297	0.015
32	5.30	0.263	0.013

The results from Tables 5 and 6 are displayed in graphical form in Figure 17.

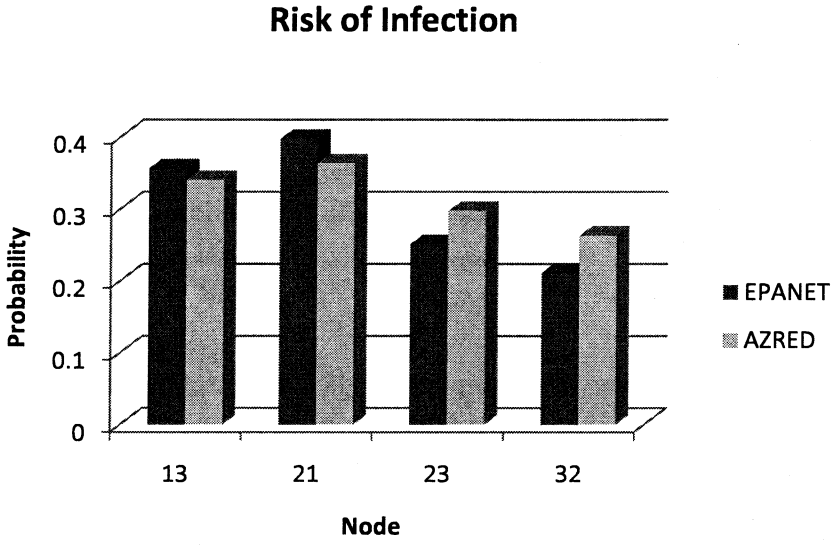

Figure 17. Comparison of EPANET and AZRED II: Risk of infection per node.

It is evident from the data exhibited in Figure 17 that upstream nodes 13 and 21 present a greater risk of infection when EPANET is used to generate simulations, while downstream nodes 23 and 32 present a greater risk of infection when AZRED is used. Table 7 exhibits the difference in the probability of risk with regard to AZRED in comparison to EPANET.

Table 7. Risk differences with regards to AZRED II in comparison to EPANET.

Node	Percent Difference
13	-4.60%
21	-8.95%
23	16.79%
32	21.94%

As shown in Table 7, AZRED II calculates a greater probability of infection associated with downstream nodes 23 and 32. EPANET calculates a greater probability of infection associated with upstream nodes 13 and 21.

CHAPTER 4

DISCUSSION

This study presents a comparison of two water quality modeling tools: EPANET and AZRED. AZRED I and II are novel in that realistic water quality behavior is taken into consideration. In addition, this study focuses on a realistic scenario involving a contaminant—in this case, *Cryptosporidium*—in order to present a clear comparison of the water quality programs. Lastly, the study employs risk assessment techniques to calculate the subsequent location-based infection risk within 24 hours of a *Cryptosporidium* intrusion into a drinking water system.

EPANET includes two assumptions regarding water quality. The first assumption—complete mixing occurs at pipe cross junctions—is incorporated into AZRED I. The second assumption, axial dispersion, is not incorporated into EPANET but has been recently added to AZRED II by the Choi group at The University of Arizona. For the purposes of this particular study, axial dispersion is a critical characteristic because including it can improve accuracy when predicting health risks caused by an infectious contaminant.

4.1 Testing of AZRED II

The first portion of this study involved a thorough testing and troubleshooting of AZRED II with regard to laminar flow conditions. While AZRED II has been developed solely for simulating laminar conditions, it is currently undergoing a process that will add methods for calculating transitional and turbulent conditions. The AZRED II testing

produced unforeseeable results. These results were discovered in graphical form, in which the contaminant concentration exhibited asymptotic behavior. However, several modifiable parameters were found, and these allowed for more desirable results. These parameters included a Reynolds number, a demand pattern, and quality tolerance. The combination of the modified parameters produced the best scenario to include and use in the risk assessment portion.

This study is a location-based risk assessment performed for the purpose of considering a significant public health issue while testing and applying a newly developed water quality modeling tool. The results convey several notable points.

4.2 EPANET and AZRED Concentration Data

With respect to the concentration versus time data per location, the results generated by EPANET differ greatly from those generated by AZRED, as shown in Figure 16. *Cryptosporidium* has a wide infectivity range—10 to 100 oocysts—for individual infection, and as a result, contaminant dispersion may not make a significant difference in terms of calculating the probability of infection. However, using AZRED as opposed to EPANET when considering other biological or chemical contaminants that can be lethal in small doses—contaminants such as anthrax or cyanide—may produce more valuable outcomes.

Calculating the concentration of contaminant is useful in predicting the potential shut off of the water system. When discussing *Cryptosporidium* which must be ingested in high concentrations, it is important to accurately estimate the concentration to be

prepared to shut off a part of the water system. The axial dispersion included in AZRED represents a smaller concentration of contaminant over a longer period of time. So, in the case of *Cryptosporidium*, AZRED calculations would be significant in preventing unnecessary events involving the shutdown of water systems.

4.3 Risk Assessment

The risk assessment technique employed in this study accounts for contaminant ingestion at a specific location over the course of 24 hours. An intrusion simulated using EPANET is regarded as a pulse at any location and at any time, while an intrusion simulation using AZRED is regarded as a dispersive curve with a smaller peak concentration, and the presence of contaminant is presumed to remain present for a longer period of time. Considering the consumption pattern that typically occurs over a 24-hour span, the resulting mass of *Cryptosporidium* ingested will be similar regardless of whether the simulation was run in EPANET or AZRED. However, this risk assessment is location-based, and hence, the risk of infection varies from node to node. It is evident that the effects of AZRED are more prominent downstream from the intrusion, as can be observed from the percent differences in Table 7. This may be due to not only dispersive effects, but also because of incomplete mixing at cross junctions.

AZRED accounts for small contaminant concentrations over a larger period of time, so in an exposure time-based simulation, the accuracy of AZRED would be beneficial in predicting contaminant concentration and the subsequent risk of infection. Additionally, the dose-response models chosen in order to calculate risk reflect greatly on

the result. In this study, the Bayesian hierarchical exponential model was used with *Cryptosporidium* dose-response parameters provided by Mitchell-Blackwood et al. (2010). The risk of infectivity could vary greatly, depending on either the model used or the parameter values included. This particular study included the 95th percentile and median values; however, depending on the parameter values, the predictive risk of infection could significantly change.

4.4 Improvements

This interdisciplinary study is the first step towards using water quality models to predict waterborne infection. The initial AZRED II simulations revealed unexpected outcomes and led to the modification of several parameters in order to reduce errors when performing the risk assessment. The unusual results were due to discrepancies in the source codes of EPANET and AZRED. These discrepancies are discussed in further detail in the Appendix. AZRED II is a novel water quality model that is still in the process of being developed, and other unexpected issues likely will be discovered and resolved in the future. Additionally, utilizing a larger network for the simulations could reveal useful data. The EPANET Example Network 1 used in this study included one cross-junction; however, a larger network with more than one cross-junction could provide significant data.

The risk assessment techniques utilized in this study are solely location-based. However, the application of a time-based method may allow for a greater distinction between results obtained via EPANET versus the results obtained via AZRED. In

particular, a time-based method would allow for a determination of specific infectivity at a specific time at a specific location. For the purpose of this study, however, a location-based risk assessment allows for an estimate of individual infectivity at a particular location in a water distribution network. A location-based risk assessment is the first step towards utilizing a newly developed water quality modeling tool.

4.5 Applications and Future Studies

This study tested and applied a novel water quality modeling program in order to complete a microbial risk assessment. AZRED takes into consideration realistic water quality behavior, thereby allowing for more accurate concentration calculations after the occurrence of a contaminant intrusion. While the program is still under development, it accurately represents axial dispersion in laminar flow conditions. Testing revealed unusual results that are acknowledged in order to represent realistic water quality behavior. AZRED has the potential to change water quality modeling in the future and risk assessment as well, because the concentration data could be used to determine the corresponding risk of infection. Utilization of a realistic water quality model will allow for the prediction of biological or chemical contaminant infection at small concentrations for a longer period of time, rather than a large pulse for a short amount of time.

The ability to predict and act upon a contaminant intrusion, which is a significant public health issue, could lead to the elimination of large-scale infections in the future. Further, AZRED could be used to determine the optimal locations for sensors that can be set to detect a specific concentration of contaminant, or a detection limit, in order to stop

water flow in one or several sections of the distribution system. Finally, in the event of a contaminant intrusion, an organizational plan could be developed regarding water flow at a particular section of the network. AZRED has the potential to reduce waterborne infection and thereby significantly have a positive impact on public health in the future.

APPENDIX A: Troubleshooting Methods

The simple network simulations were performed to troubleshoot a significant issue that was discovered during AZRED II testing. AZRED II testing exhibited asymptotic behavior due to residual concentrations in the pipes and a corresponding large mass balance percent error. The mass balances were initially verified with the simple network for a 72-hour simulation. Unlike EPANET and AZRED I, AZRED II simulations resulted in a significantly greater contaminant mass leaving the system versus contaminant mass into the system. The simulation time was longer than 24 hours in order to observe the effects of the residual contaminant concentrations occurring in AZRED II simulations. These calculations were performed on the EPANET results and compared to the AZRED I and II results.

Table A.1. Mass balances and errors for EPANET, AZRED I, and AZRED II.

EPANET	Mass In (mg)	Mass Out (mg)	% Error	AZRED I	Mass In (mg)	Mass Out (mg)	% Error	AZRED II	Mass In (mg)	Mass Out (mg)	% Error
Node 10	5251.84	0.00		Node 10	2625.92	0.00		Node 10	5251.84	0.00	
Node 13	0.00	2646.88		Node 13	0.00	2646.88		Node 13	0.00	6296.30	
Total	2625.92	2647.63	0.83	Total	2625.92	2646.88	0.80	Total	5251.84	6296.30	19.89

The node closest to the intrusion exhibited an oscillating behavior. This is graphically exhibited in Figure A.1. Observation of oscillating behavior provided the explanation that the asymptote could be a representation of noise. Hence, eliminating the asymptote could produce a greater accuracy.

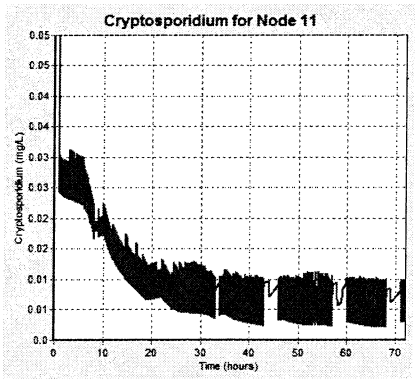

Figure A.1. Node 11 concentration data via AZRED II.

Parameter modifications were made one at a time in an attempt to eliminate the asymptotic residuals. The first change involved the length of pipe 10, which was modified from 0.5 feet to 9 feet. The result of this modification is exhibited in Figure A.2. The next change involved decreasing the quality time step from 1 minute to 10 seconds. The water quality time step dictates how often results are recorded. Decreasing the quality time step allows the simulation results to be more accurate. Additional changes made during the troubleshooting process involved manually eliminating the asymptotes, increasing flow rate throughout the system, decreasing simulation time, changing the simulation start time, and decreasing the quality tolerance. Mass balances and subsequent errors were calculated in order to check the accuracy after each parameter modification in the AZRED II simulations. Additionally, the modifications were made to EPANET simulations in order to compare them with the AZRED II results. An error within 10% was considered acceptable.

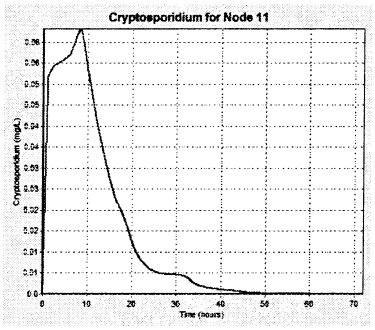

Figure A.2. Node 11 concentration data via AZRED II.

Table A.2. Mass balance and corresponding error for AZRED II.

AZRED II	Mass In (mg)	Mass Out (mg)	% Error
Node 10	2625.92	0.00	
Node 13	0.00	3626.61	
Total	2625.92	3626.61	38.11

The oscillations significantly diminished after the length of the first pipe was increased from 0.5 feet to 9 feet. Although the noise was reduced, the error increased. The concentration was achieving an asymptote rather than reaching zero.

The quality time step determines the interval of time between each recording of the contaminant concentration at a particular location. A smaller time step results in more accurate concentration readings. The quality time step was therefore decreased from 1 minute to 10 seconds. Figure A.3 displays the change exhibited in Node 11.

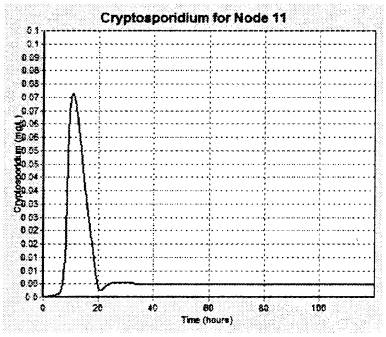

Figure A.3. Node 11 concentration data via AZRED II with decreased time step.

The simulation time was increased from 72 hours to 120 hours to further observe the asymptotic behavior. In order to test whether or not the asymptotes were causing the significant error, the asymptotes were removed and the resulting mass balances were analyzed. The results are shown in Table A.3. The resulting percent error was similar to that calculated with the inclusion of the asymptotes.

Table A.3. Mass balance and corresponding percent error for AZRED II.

AZRED II	Mass In (mg)	Mass Out (mg)	% Error
Node 10	2427.32	0.00	
Node 13	0.00	3350.08	
Total	2427.32	3350.08	38.02

The next test involved the flow rate. While it was necessary for the system to be in laminar flow with a Reynolds number of less than 2100, the flow rate had the potential to increase. The goal of the next test involved increasing the flow rate in order to reach a Reynolds number of at least 1500. With a higher flow rate, less residual contaminant would be present in the pipes, hence reducing the likelihood of asymptotic behavior. In order to increase the flow rate, nodal demand and pipe diameter were decreased. Optimal values were determined based on numerous simulations. This specific experimental run involved calculating the mass balances including and excluding the asymptotes.

Table A.4. AZRED II simulation including asymptotic residuals.

AZRED II	Mass In (mg)	Mass Out (mg)	% Error
Node 10	24.98	0.00	
Node 13	0.00	105.65	
Total	24.98	105.65	322.91

Table A.5. AZRED II simulation eliminating asymptotic residuals.

AZRED II	Mass In (mg)	Mass Out (mg)	% Error
Node 10	24.98	0.00	
Node 13	0.00	28.95	
Total	24.98	28.95	15.87

Increased flow in the pipes was achieved by decreasing the populations and by decreasing the pipe diameters to still attain laminar conditions. It was found that a Reynolds number closer to 2100 resulted in less residual contaminant in the pipes. Very low flow rates contributed to slower contaminant travel, and the tendency for the contaminant to stick to the pipe walls, a phenomenon that occurs when the Reynolds number is in the lower laminar flow range. Graphically, low flow rates resulted in asymptotes.

The simulation time was decreased from 72 hours to 24 hours. The reason for increasing the simulation time with AZRED II was to observe the full dispersive effect; however, the residual concentrations are not considered to be useful, so decreasing the simulation time does not negatively impact the concentration calculations. Decreasing the simulation time also more clearly displays the dispersive effects of AZRED II in graphical form.

The previous simulations were based upon time zero representing 12:00 AM. Time zero represents the start of the simulation, and in this study, time zero also represents the time of the *Cryptosporidium* intrusion. The intrusion, however, can be set to occur at any time. For the rest of the simulations in this study, time zero was set to 7:00 AM. With the simulation time beginning at 12:00 AM, the water flow is low, since water usage from 12:00 AM to 6:00 AM is sparse. As a result of beginning the simulation

with low water flow, the contaminant concentration upstream was low. It is beneficial, in terms of modeling, to avoid such a situation. A slight modification of the simulation start time results in a sharper concentration curve and, hence, results in a lesser occurrence of residual concentrations in the pipes. As shown in Table A.6, the percent error was low with the inclusion of the asymptotes. Hence, a simulation excluding the residuals was not performed. A slight modification to the demand pattern impacted the results significantly. While the change yielded the best results in terms of an improved mass balance and less asymptotic behavior, upon further modification of the AZRED II source code, the intrusion and simulation start times will be more freely modified with equally accurate results.

Table A.6. AZRED II with modified demand pattern inclusive of asymptotic residuals.

AZRED II	**Mass In (mg)**	**Mass Out (mg)**	**% Error**
Node 10	628.69	0.00	
Node 13	0.00	695.27	
Total	628.69	695.27	10.59

Quality tolerance was the last parameter modified during the troubleshooting process. This parameter is associated with the differing quantitative approaches taken in EPANET and AZRED. EPANET utilizes the Eularian approach, which is used to observe, in this case, fluid flow at a particular time. The Eularian approach is analogous to a series of photographs taken at a fixed location in order to observe the change in fluid flow with respect to time. AZRED utilizes the Lagrangian approach, in which a specific portion, rather than the entire field, of the fluid flow is observed with respect to time. In this regard, flow behavior quantified by EPANET versus AZRED may not be equivalent. While modifying quality tolerance in the simulations may reduce the error, the AZRED

source code must take into consideration the transition between the Eularian and Lagrangian approaches.

Determining quality tolerance requires the creation of a new pipe segment depending on the concentration in the pipe. Within each pipe segment is a uniform contaminant concentration, but concentrations differ from one pipe segment to another. The quality tolerance is the smallest change in concentration that will require either the creation of a new segment or the continuation of an old segment. Segment creation or continuation only occurs at pipe junctions. With regard to small concentrations, decreasing the quality tolerance creates segments and results in a higher accuracy. The quality tolerance was tested for every 10^{-1} decrease, starting with 0.1. Figure A.4 represents the graphical result of modified quality tolerance and Table A.7 displays the resulting mass balances and errors calculated. Quality tolerance was the only parameter that eliminated the asymptotic behavior. Because the asymptotes were removed without having to manually eliminate data points, the resulting mass balances were within a reasonable percent error of 10%.

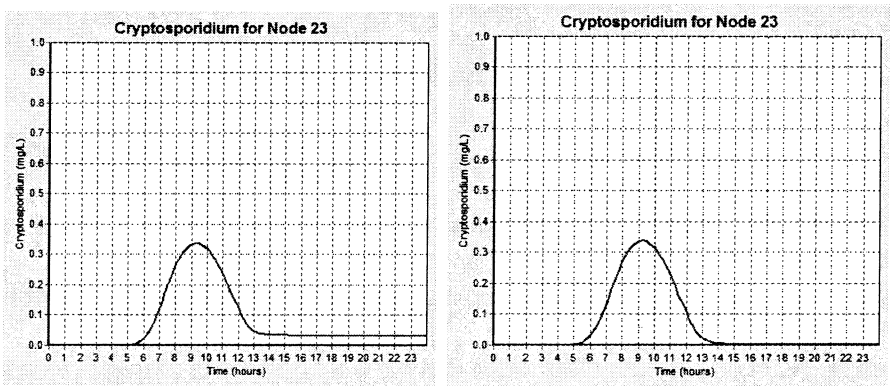

Figure A.4. Left: AZRED II simulation with quality tolerance of 0.01. Right: Simulation with quality tolerance of 0.001.

Table A.7. AZRED II mass balances and corresponding errors with modifications to quality tolerance.

Quality Tolerance: 0.01	**Mass In (mg)**	**Mass Out (mg)**	**% Error**
Node 10	3772.89	0.00	
Node 13	0.00	639.06	
Node 21	0.00	615.57	
Node 23	0.00	1314.09	
Node 32	0.00	1256.82	
Total	3772.89	3825.53	1.40

Quality Tolerance: 0.001	**Mass In (mg)**	**Mass Out (mg)**	**% Error**
Node 10	3772.89	0.00	
Node 13	0.00	565.91	
Node 21	0.00	561.08	
Node 23	0.00	1154.60	
Node 32	0.00	1124.42	
Total	3772.89	3406.02	-9.72

The quality tolerance of 0.01 was used for the microbial risk assessment portion of the study.

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